Paleoseismic Investigation of the Northern San Gregorio Fault, Half Moon Bay, California

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INVESTIGATIONS UNDERTAKEN

The San Gregorio fault system is an active, northwest-trending right lateral strike slip fault zone located approximately 14-km west of the San Andreas fault in coastal San Mateo County, California (Figure 1). Despite geomorphic and paleoseismic evidence of Holocene activity (Koehler et al., 2004; Simpson et al., 1997; Simpson and Knudsen, 2000), data on the timing and recurrence of past earthquakes along the northern San Gregorio fault (SGF) is limited. Earthquake recurrence data are essential for evaluating the seismic potential of the San Gregorio fault.

In our first year study (Koehler et al., 2004), we extracted seven vibra-cores from Pillar Point marsh. Marsh stratigraphic and paleoecological data obtained in the cores were used to identify two and possibly four earthquake-induced subsidence events along the northern SGF. A radiocarbon date on the stratigraphically highest subsided marsh soil indicates that the most recent earthquake (MRE) occurred between AD 1667 and 1802. Based on the results of the first year study, we initiated the current investigation to: (1) confirm and refine the timing of the MRE and older paleo-earthquakes on the SGF, and (2) conduct comparative stratigraphic studies to validate the approach of using marsh stratigraphy in paleoseismic studies on strike-slip faults. To address these objectives, we conducted additional stratigraphic, radiometric, and paleoecological studies at Pillar Point marsh, performed a conventional paleoseismic trench investigation directly north of the marsh, and examined marsh stratigraphy in a marsh not associated with an active fault. We were assisted in our field work by Sean Sundermann, Justin Pearce, and Ashley Streig of William Lettis & Associates.

The northern on-land trace of the SGF extends from Pillar Point to Moss Beach and appears to consist of three en echelon, right-stepping fault traces (Figure 2). Based on geomorphic expression and sea cliff exposures, the western-most on-land trace extends across the headland of Pillar Point. The middle fault trace extends along the western edge of Pillar Point marsh and through the middle of Seal Cove Bluffs. The location of this trace is inferred from small faults in the seacliff and a linear swale and saddle on the Pillar Point headland. The eastern fault trace extends from the eastern edge of Pillar Point marsh to Moss Beach, and is geomorphically well-expressed as a northeast-facing escarpment over 30-meters high along the east side of Seal Cove Bluffs (Figure 2). Pillar Point marsh lies within an inferred pull-apart structure between the middle and eastern fault strands (Figure 2) and records evidence of subsidence in the form of buried marsh soils that are abruptly overlain by intertidal mud deposits (Koehler et al., 2004; Simpson and Knudsen, 2000).

In March, 2004, we performed a reconnaissance survey consisting of three 2.5-cm diameter gouge cores and one 7.6-cm diameter vibra-core oriented along a transect across China Camp marsh, a quiet water, relatively stable environment within San Pablo Bay, the northern lobe of the greater San Francisco Bay (Figures 3 and 4). We also evaluated the possibility of coring Rodeo Lagoon in the Marin Headlands, a relatively stable coastal marsh east of the San Andreas fault with a low rate of uplift. However, based on review of wetland studies at Rodeo Lagoon that documented large volumes of coarse grained historic sedimentation in the marsh, it was determined that further stratigraphic studies at Rodeo Lagoon would not yield the type of information needed to document the late Holocene evolution of this non-tectonic marsh. Additionally, in association with John Boyle (Liverpool University), we performed a reconnaissance subsurface stratigraphic investigation of Pescadero Marsh, a large estuary within the San Gregorio fault system. The purpose of these surveys was to asses the differences in stratigraphy between Pillar Point marsh and other marshes not influenced by tectonics in order to develop distinct criteria to evaluate whether tectonic subsidence is the best explanation for the observed buried marsh soils at Pillar Point.

We extracted an additional 3.6-meter deep vibra-core from Pillar Point marsh to gain a more complete understanding of both the environment of deposition and time of depositon for estuarine sediments preserved in the marsh. The core was described, photographed, and sampled. Radiometric and paleoecologic samples collected from this core and from cores preserved from our first year investigation were submitted. Radiocarbon analysis of eleven bulk sediment samples has been completed by Beta Analytic and we are currently awaiting results of ten detrital macrofossil samples submitted to Dr. Gordon Seitz through the U.S. Geological Survey. Additionally, paleoecologic samples submitted to EHH Consulting Micropaleontology have been analyzed (Nov. 2004). These data combined with our past results at the site will help us correlate buried marsh soil horizons across the marsh and assess whether these horizons were submerged by tectonic subsidence.

<u>Trenching Investigations</u>
In October, 2004, we excavated two trenches located approximately one kilometer north of Pillar Point marsh. The purpose of the trench investigations was to document geological evidence for prehistoric earthquakes, evaluate the possible relationship between paleoearthquakes on the San Gregorio fault and evidence for sudden marsh submergence at the Pillar Point marsh, and assess the style of faulting to test the proposed model that right-stepping, en echelon faults form small extensional basins, like Pillar Point marsh, along the base of Seal Cove Bluff. After clearing the proposed sites for underground utilities, the trenches were excavated using a standard rubber-tire backhoe and shored according to Cal-OSHA regulations. Detailed logs drawn between 1:20 and 1:40 scales documented the stratigraphic and structural relationships exposed in the trenches.

PRELIMINARY RESULTS

The China Camp marsh site (Figure 3) was chosen to obtain stratigraphic data for a marsh not associated with an active fault and, thus, not likely to be influenced by vertical tectonic-related land-level changes. The purpose of obtaining marsh stratigraphic data from this non-tectonic marsh is to demonstrate distinct differences in the stratigraphic record between a marsh responding to slow sea level rise (China Camp) and a marsh that responds to sea level rise overprinted by inferred tectonic subsidence events (Pillar Point). This comparison independently assesses the tectonic subsidence mechanism for the buried marsh soils observed at Pillar Point Marsh.

The marsh site is located within China Camp State Park along the southeastern shore of San Pablo Bay, north of Buckeye Point, approximately 3 miles northeast of the city of San Rafael, Marin County, California (Figures 1 and 3). Directly west of the marsh the topography is dominated by San Pedro Ridge, a northwest trending ridge line characterized by steep, rugged hillslopes drained by numerous ephemeral streams. These hillslopes are composed of blocks of Cretaceous age sandstone and shale that strike northeast-southwest and dip between 60 to 30 degrees northwest (Blake et al., 2000). The topography of the marsh is flat with the exception of four small hills named Jake's Island, Turtle Back Hill, Bullet Hill, and Chicken Coop Hill. These hills are composed of Jurassic Age Franciscan mélange consisting of sheared shale and sandstone with inclusions of greenstone, chert, greywacke, and serpentinite (Blake et al., 2000). Stream valleys directly north of Turtle Back Hill and directly south of Bullet Hill contain Holocene alluvium that has been incised by ephemeral streams that grade to the marsh surface and meander across it.

The stratigraphic sequence identified in China Camp marsh consists of a relatively continuous record of intertidal mud deposition interbedded with thin, tidal marsh soils (muddy peaty and peaty muds), and sandy mud storm deposits (Figure 4). Intertidal mud deposits consist of massive, olive gray to olive brown silt loam with common thin (< 3 mm thick) laminae. Laminae consist of charcoal-rich layers and muddy peat deposits. Tidal marsh soils observed in the cores consist of muddy peat deposits generally less than 1-2 cm thick interbedded with intertidal mud. These deposits occur at three locations in the core and show a gradual increase followed by a gradual decrease in peat concentration. We infer that these gradual transitions represent slow marsh response to gradual fluctuations in the rate of sea-level rise in the late Holocene. The absence of thick buried peat deposits abruptly overlain by thick mud deposits (i.e. Pillar Point Marsh) indicates that the China Camp marsh surface has not experienced sudden subsidence. Based on this fundamental difference in stratigraphy, we infer that the tectonic subsidence mechanism for the buried soils observed at Pillar Point Marsh is a valid interpretation. Following completion of Pescadero Marsh core analysis (Dr. John Boyle, Liverpool University), we will also compare our Pillar Point and China Camp data to this new data set.

In order to further correlate stratigraphy at the Pillar Point marsh site and collect new radiocarbon and diatom samples, we extracted an additional vibracore from Pillar Point marsh. Stratigraphic sequences observed in this new core strengthen stratigraphic correlations identified in our previous cores at the site and consist of buried tidal marsh soils (peats), alluvial channel deposits, intertidal mud, and beach deposits. The buried marsh soils have sharp to gradual upper contacts and are overlain by intertidal mud and peaty mud. We are currently awaiting the results of paleoecological analyses of diatoms that will be used to assess changes in the depositional environment possibly related to subsidence during earthquakes. Radiocarbon analyses indicate that the marsh first became inundated by the sea 3890 +/- 40 years BP. Marsh soils were abruptly buried by rapid relative sea level rise at 170-400 years BP (Peat 1) and 3190-3680 years BP (Peat 6). Stratigraphic data indicates the possibility that two additional subsidence events (Peats 3 and 4) occurred between these two events. Based on criteria developed by Nelson et al. (1996) and modified by Knudsen et al. (2002) and Koehler et al. (2004), we infer that these rapid burial events are related to tectonic subsidence during earthquakes on the SGF. Criteria used in our analysis include, abrupt upper lithologic contact, lateral extent of submergence, diatom evidence for relative sea level rise, evidence for sustained submergence and/or rapid aggradation, and synchroneity with nearby evidence of paleoseismic events. Evaluation of the diatom data is underway and will be used to substantiate the chronology of tectonic events developed in our first year study and assess the tectonic subsidence mechanism for burial of Peats 3 and 4. We are currently evaluating the radiocarbon results and preparing a Final Technical Report.

Preliminary observations from trench exposures

Trench 1 was located at the base of the prominent linear escarpment along the eastern margin of the Seal Cove Bluffs (Figure 2). The trench was about 30 m long and ranged from 3 to 5 m deep. We sited the excavation across a low-relief debris fan that periodically receives sediment evacuated from a colluvial hollow upslope to investigate possible deformation of latest Holocene colluvial strata. Prior trench investigations by Berlogar, Long & Associates in 1981 confirmed the presence of active fault-related deformation of deposits that underlie the debris fan. Unexpectedly, we encountered an archeological deposit within the upper 0.7 to 1.3 m of the exposure that was identified by California State Park archeologist Mark Hylkema as a prehistoric shell midden deposited by native Californians. This cultural deposit provides a useful chronostratigraphic datum that will be used to constrain the timing of the most recent deformation on the fault.

Trench 2 was located approximately 280 m northwest of trench 1 and approximately 50 m east of the escarpment. Trench 2 was about 22 m long and about 3.7 m deep at its deepest point. The trench was sited based on a consulting report by Berlogar, Long & Associates (1981) that concluded that a second fault traversed the broad alluvial plain east of Seal Cove Bluff parallel to the primary fault at the base of the escarpment. The purpose of trench 2 was to investigate this secondary fault to evaluate the style of deformation and document possible evidence for the most recent earthquake. Sediments encountered in the trench are interpreted to be gravelly sands of the ca. 80 ka Half Moon Bay terrace and overlying poorly sorted, fine-grained Denniston Creek fan sediments.

Stratigraphic and Structural Relationships

Trench 1

Strata encountered in trench 1 are draped across the base of the east-facing escarpment of the Seal Cove Bluffs and include interbedded colluvial, marsh and archeological deposits. Trench exposures contained no bedrock. The lithology of the colluvial deposits ranges from sandy clay to clayey silt with gravel. Clasts within the colluvium consist predominantly of Purisima Formation fragments eroded from bedrock exposed in the escarpment directly to the west. Rarely, gravel-sized clasts included rounded chert pebbles, and angular feldspar and quartz crystals likely reworked from Pleistocene marine terrace deposits that mantle the top of the Seal Cove Bluffs. With the exception of several prominent stone lines, there was a notable lack of internal stratigraphy within the colluvium. A thick cumulative soil profile consisting of a series of A horizons developed in the upper 3.5 to 4 m of colluvium implies that the colluvium was deposited in the middle to late Holocene and suggests that periodic debris flows gradually built up the debris fan through time preventing the development of mature soil profiles.

In the deepest part of the trench black, organic-rich mud onlap and interfinger with the colluvial deposits. We tentatively correlate these muddy deposits with the prominent black soil observed in the base of cores from Pillar Point marsh studied during year one of this project. The mud contains angular sandstone clasts of the Purisima Formation as well as some quartz and feldspar clasts likely derived from terrace remnants exposed in the escarpment to the west. The fine-grained lithology and rich organic nature of the mud suggests it was deposited in a marsh impounded on the west by the Seal Cove Bluffs. Colluvial deposits grade laterally, from west to east, into the marsh deposits and suggest that the western margin of the marsh migrated eastward as the colluvial deposits prograded out over the marsh and eventually completely buried the marsh.

Archeological deposits encountered in the eastern end of trench 1 range from 0.5 to 1.5 m thick and consist of silty colluvium with 10 to 30 percent fragmented shells of marine invertebrates and rarer fragments of mammal bone and stone artifacts. The shell debris is concentrated toward the base of the unit where evidence for bioturbation suggests that some mixing with the underlying units has occurred. The clear, subplanar lower contact of the midden is the youngest strata offset by a fault observed in the trench. This shell midden shares many characteristics with native Californian cultural deposits dated at A.D. 1270 to 1400 at the Seal Cove trench site studied by Simpson et al. (1997).

Three thrust faults offset thick, poorly stratified Holocene colluvial deposits in trench 1. Each fault dips from 16° to 36°SW and shows an apparent reverse sense of slip with west-side-up vertical separation. No slickensides were observed on fault planes that would indicate the absolute slip direction. For clarity in the discussion, we assign each fault a letter from A to C. Fault A offsets only the oldest deposits exposed in the trench. Fault B offsets slightly younger deposits than fault A. Fault C, the fault with the largest amount of displacement, offsets the youngest deposit in the trench—a late Holocene archeological shell midden.

Fault A is a low-angle thrust fault that strikes N48°W and dips 21°SW. East-vergent apparent reverse slip on this structure places weathered, clayey colluvium over black marsh deposits. Measured displacement of the base of the marsh deposits provides an apparent dip-slip offset estimate of 0.6 to 1.0 m. Although the fault tip appears to terminate in the marsh deposits, it is possible that the fault either is continuous with or truncated by fault C. The massive, homogenous nature of the marsh mud obscures the structural relationship, if any, between fault A and fault C. Anticlinal folding of deposits directly above the fault tip also may be related to slip on fault A.

Fault B is a low-angle secondary fault in the hanging wall of fault A that strikes N27°W and dips 21°SW. The oldest colluvial deposits exposed in the trench are folded and possibly faulted over younger colluvial deposits. In the northern trench wall, offset of the base of unit 20B suggests about 0.6 m of apparent reverse displacement combined with possible kink folding of the base of unit 40B. The southern trench wall shows similar kink-fold deformation but no evidence for significant offset of the base of unit 20B. The observation that the kink fold coincides with the end of the western limb of the anticline overlying fault A suggests that deformation on the two structures was coeval.

Fault C has the largest amount of displacement of the three faults and offsets a shell midden that records prehistoric habitation by native Californians. This thrust fault strikes N62°-70°W with a low-angle westward dip (16°-36°SW) that becomes progressively steeper with depth. The fault plane was examined for evidence of oblique slip, but no slickensides were observed. Near the bottom of the trench, drag folding related to reverse slip along the fault deforms interbedded colluvial and marsh deposits. Apparent dip-slip displacement of the base of unit 30 is at least 0.75 m not including deformation by folding. Displacement of the base of unit 50, which shows less evidence for folding, is about 1.35 m. Vertical separation of unit 30 ranges between 1.5 to 1.8 m. The fault continues up section, offsetting a prominent stone line marking the base of unit 70. The fault is difficult to discern through massive colluvial deposits that are largely void of internal stratigraphy. Near the top, at the eastern end of the trench, the base of the shell midden is offset 0.5 to 0.7 m along the fault. Vertical separation of the base of the shell midden is about 0.4 m. At this location fault C strikes N35°W and dips 24°SW.

Stratigraphic and structural relationships show evidence for at least two and possibly four slip events that offset probable Holocene and latest Holocene deposits. Evidence for at least two events is supported by progressively greater offset of strata along fault C with depth. For example, the vertical separation of the shell midden (0.4 m), the youngest unit offset by fault C, is three to four times less than the vertical separation of the base of unit 30 (1.5 to 1.8 m). It is possible that the deformation related to slip on fault C records three or four earthquake if each earthquake caused about 0.4 to 0.7 m of slip per event. However, we observed no stratigraphic evidence that requires an interpretation of more than two events. The exposures allow the interpretation that slip on faults A and B may have occurred concurrently with slip on fault C and therefore may record only two events. Alternatively, if the three faults operated independently, the trench exposures could record at least four earthquakes. We prefer the interpretation that faults A, B and C operated concurrently because the limbs of the fold above the tip of fault A appear to be structurally controlled by faults B and C. Radiocarbon analysis of bulk sediment samples from marsh deposits (unit 20A) and the shell midden may provide age estimates that bracket the time of faulting.

Trench 2

Strata exposed in trench 2 consist of coarse alluvial fan deposits overlain by fine-grained marsh deposits that are, in turn, overlain by 0.5- to 1-m-thick colluvial package derived from the Seal Cove Bluffs to the west. Massive, poorly sorted gravelly sands and interbedded clay layers occur in the base of the trench. Coarse sand grains and gravel clasts include quartz and feldspar lithologies derived from the Cretaceous Montara granodiorite to the east. We interpret these sediments as interbedded littoral and alluvial deposits of the 83,000 year old Half Moon Bay terrace (Weber and Lajoie, 1980). Hard, massive clay deposited on top of the terrace sediments laps onto an east-facing buried fault scarp. We interpret this massive clay as distal fine-grained alluvial deposits of Denniston Creek that were impounded against the escarpment. Colluvial silt shed from the western bluffs overlies the clay. A prominent soil developed in both the colluvial and alluvial units suggests that the landscape at trench 2 has been relatively stable for perhaps several thousand years. The soil profile includes a prominent Bt horizon characterized by well-developed prismatic peds coated with thin clay films. No charcoal or other organic material was available for radiocarbon age analysis.

Two fault zones offset latest Pleistocene alluvium of the Half Moon Bay terrace based on exposures in trench 2. The eastern fault zone offsets the lower horizons of a soil developed into fine-grained alluvial deposits that may be early to middle Holocene in age. None of the faults appeared to offset or deform the youngest colluvial deposits. Evidence for the absence of deformation of the youngest deposits coupled with the absence of fresh geomorphic scarps overlying the faults suggest that the most recent surface deformation at the site of trench 2 occurred several thousand years ago or earlier.

The eastern fault zone consists of a low-angle thrust fault that strikes N31°W and dips 25° SW. Apparent dip-slip displacement on this primary fault ranges from 0.7 to 0.8 m in alluvial deposits of the Half Moon Bay terrace. Deformation caused by folding and faulting together accommodate approximately 1.7 m of vertical separation of terrace sediments. No slickensides were observed on the fault plane to indicate absolute slip direction. The single fault strand near the base of the trench divides into several fault splays that offset fine-grained clayey alluvial deposits and a soil that overlie the gravelly terrace sands. The youngest colluvial unit that overlies the fault splays appears to be undeformed. A secondary fault strand in the hanging wall of the primary thrust fault strikes N47°W and dips 65°SW. This secondary fault offsets clayey sand beds in the oldest exposed alluvium by about 0.2 m as apparent reverse dip-slip displacement. However, vertical separation of the clay marker bed due to faulting and folding reaches up to 0.7 m. The secondary fault terminates within the oldest exposed sediments of the Half Moon Bay terrace. The width of deformation related to the eastern fault zone spans about 4 m.

The western fault zone consists of multiple fault splays that show vertical separation of alluvial deposits of the Half Moon Bay terrace. The eastern-most fault within this zone strikes N25°W and dips 70°SW. Apparent reverse displacement on this fault (west-side up) caused about 0.5 m of vertical separation of a prominent zone of iron and manganese oxide staining. Splays of the western-most fault in the zone show evidence for east-side-up vertical separation along both apparent normal and reverse faults. The primary western fault splay strikes N45°W, dips 67°SW and juxtaposes coarse-grained sandy terrace deposits against fine-grained alluvial clay. A secondary splay to the west dips about 70°E and shows about 0.05 m of apparent vertical offset. Although we observed no slickensides on any fault planes in the western fault zone, the variety of deformation styles within the zone and mismatches within the stratigraphy suggest that a significant component of lateral displacement has occurred. The western fault zone is about 2.5 m wide.

Together, the eastern and western fault zones exposed in trench 2 show evidence for east-vergent thrust and reverse faulting with corresponding hanging-wall folds and high angle faults that juxtapose different stratigraphic units. Evidence for a variety of faulting styles suggests that these structures accommodate transpressional deformation that include both right-lateral and reverse components of slip. If the western and eastern fault zones connect at depth, the width of deformation across the entire zone is about 10 m.

NON-TECHNICAL SUMMARY

Pillar Point marsh lies within a right-releasing stepover between two active traces of the on-land northern San Gregorio fault. Earthquakes on the SGF may produce abrupt coseismic subsidence and tidal submergence of the freshwater marsh. This research is designed to better understand the timing and recurrence of paleo-earthquakes on the northern SGF by evaluating lithostratigraphic, biostratigraphic, and chronologic data on marsh sediments extracted in a series of vibra-cores. Additionally, this research will independently verify and validate the approach of using marsh stratigraphy in paleoseismic studies on strike-slip faults. Our core analysis identified at least two and possibly four land level changes preserved as buried marsh soils. Pending the results of our paleontologic and radiometric analyses we will determine which land level changes are associated with tectonic subsidence and determine the age of the most recent and older paleo-earthquakes on the SGF. Pending the results of our trench investigation we will determine synchroneity of paleoseismic events between an on-land exposure of the fault and Pillar Point marsh.

REPORTS PUBLISHED

None.

DATA AVAILABILITY

Additional detailed information on the investigation is available from the Principal Investigators listed above. This information includes detailed stratigraphic descriptions of sediments cored in China Camp marsh and descriptions of trenches excavated in the vicinity of Pillar Point marsh.

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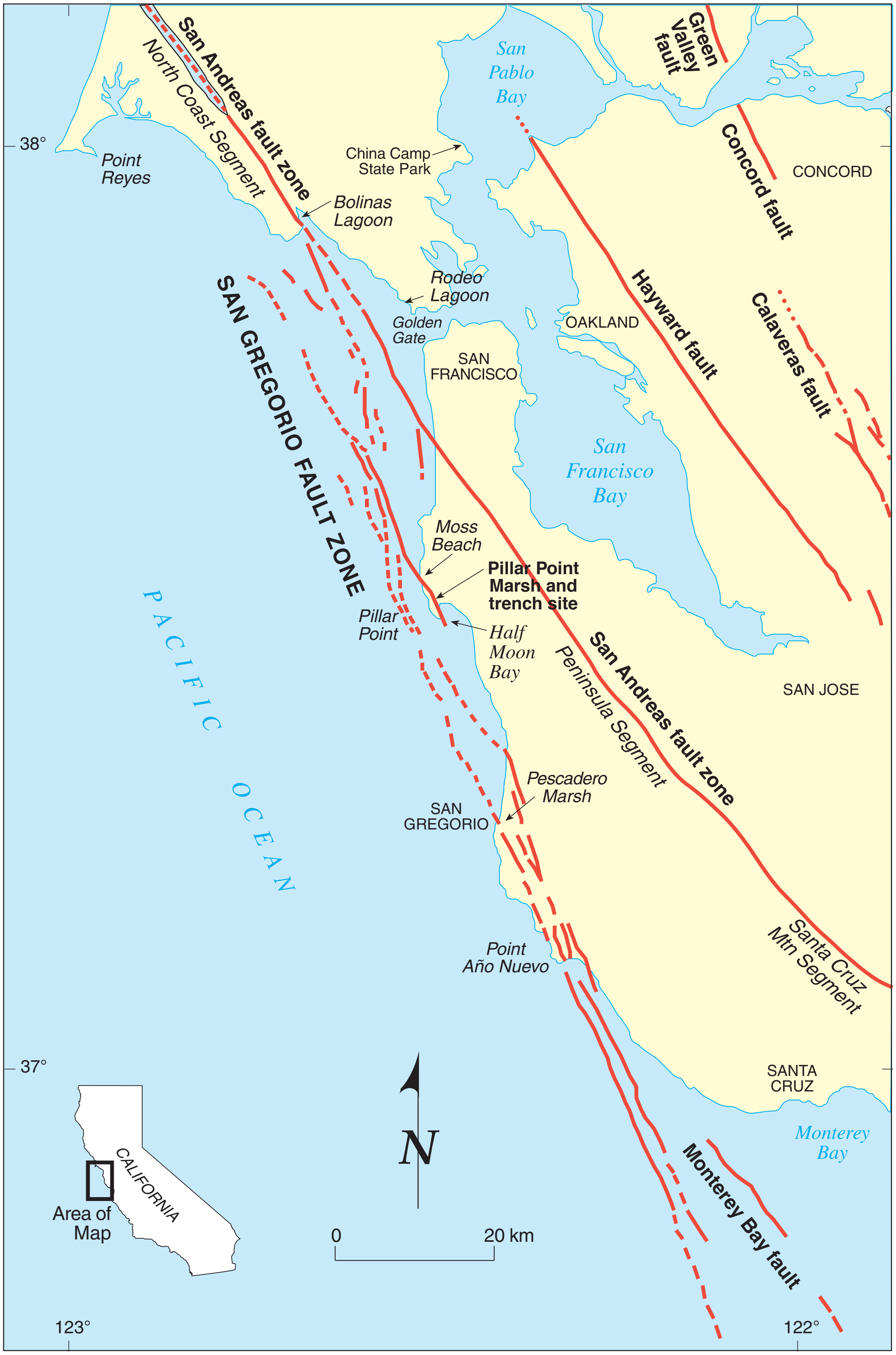
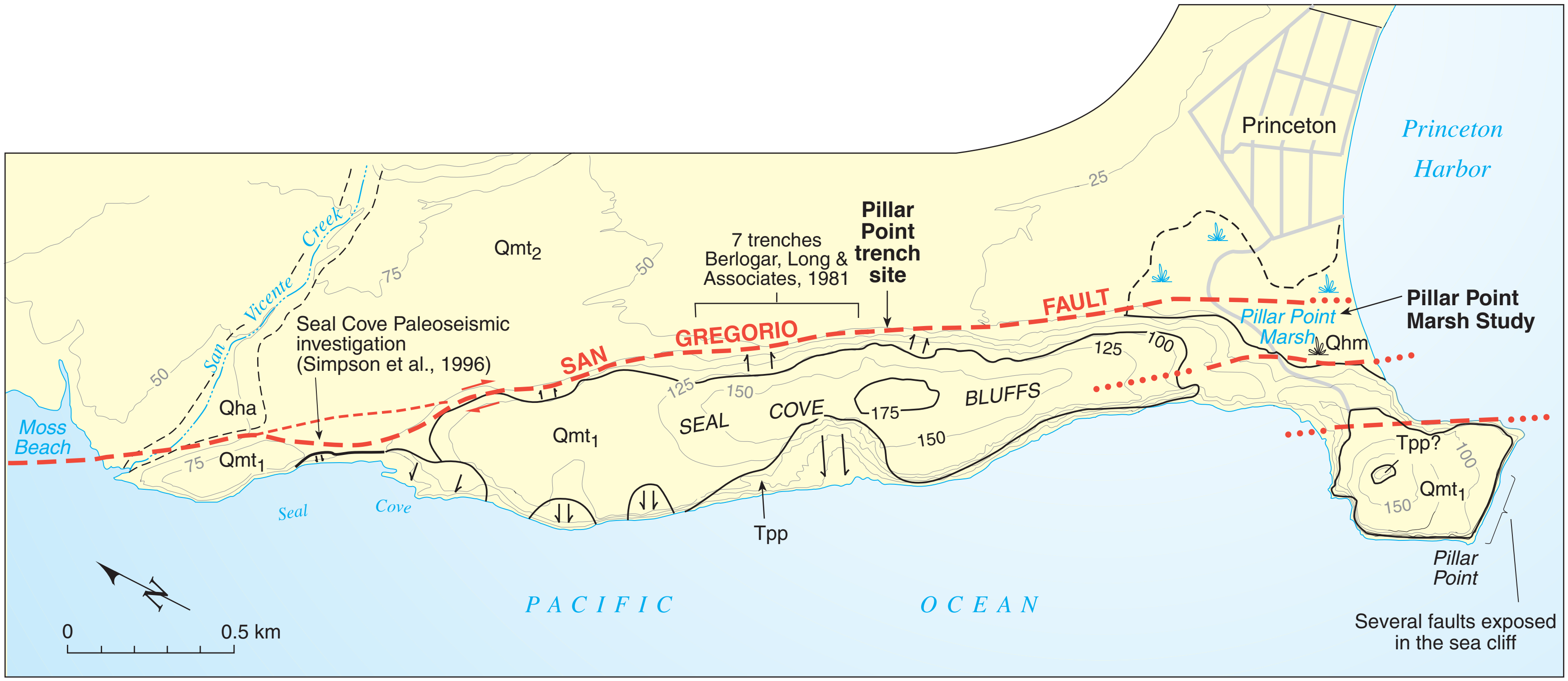


Figure 1. Map showing the San Gregorio fault zone and other principal Holocene faults in the San Francisco Bay area. Modified from Jennings (1994).



Explanation

Symbols

Northern San Gregorio Fault

Previously mapped trace of San Gregorio fault

Geologic contact; dashed where approximate

Landslide

Geologic Units

Qha	Holocene Alluvium
Qmt_2	Marine terrace, 83,000 yrs. old
Qmt_1	Marine terrace, 100,000-125,000 years old
Tpp	Purisima formation

Figure 2. Site location map.

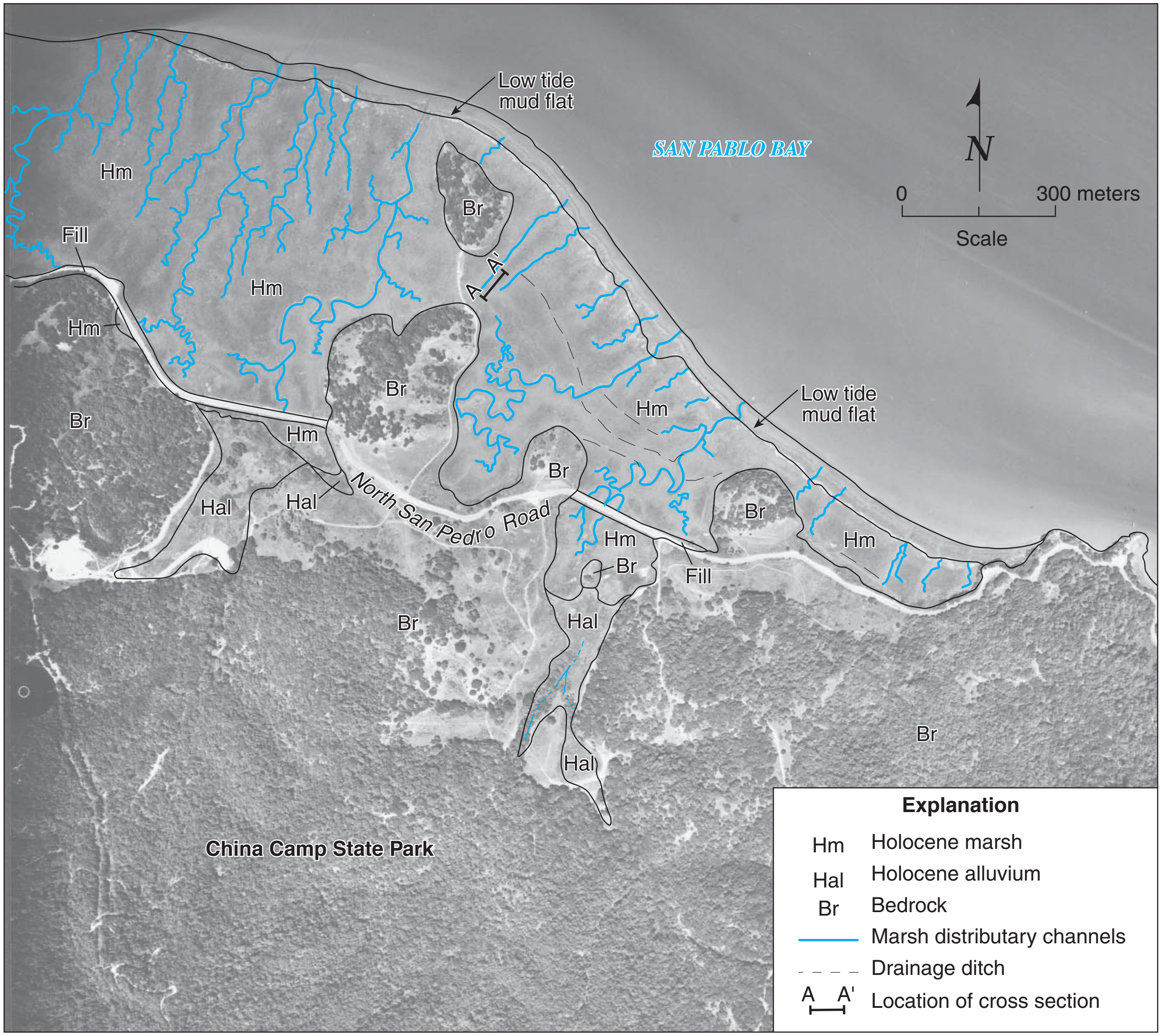
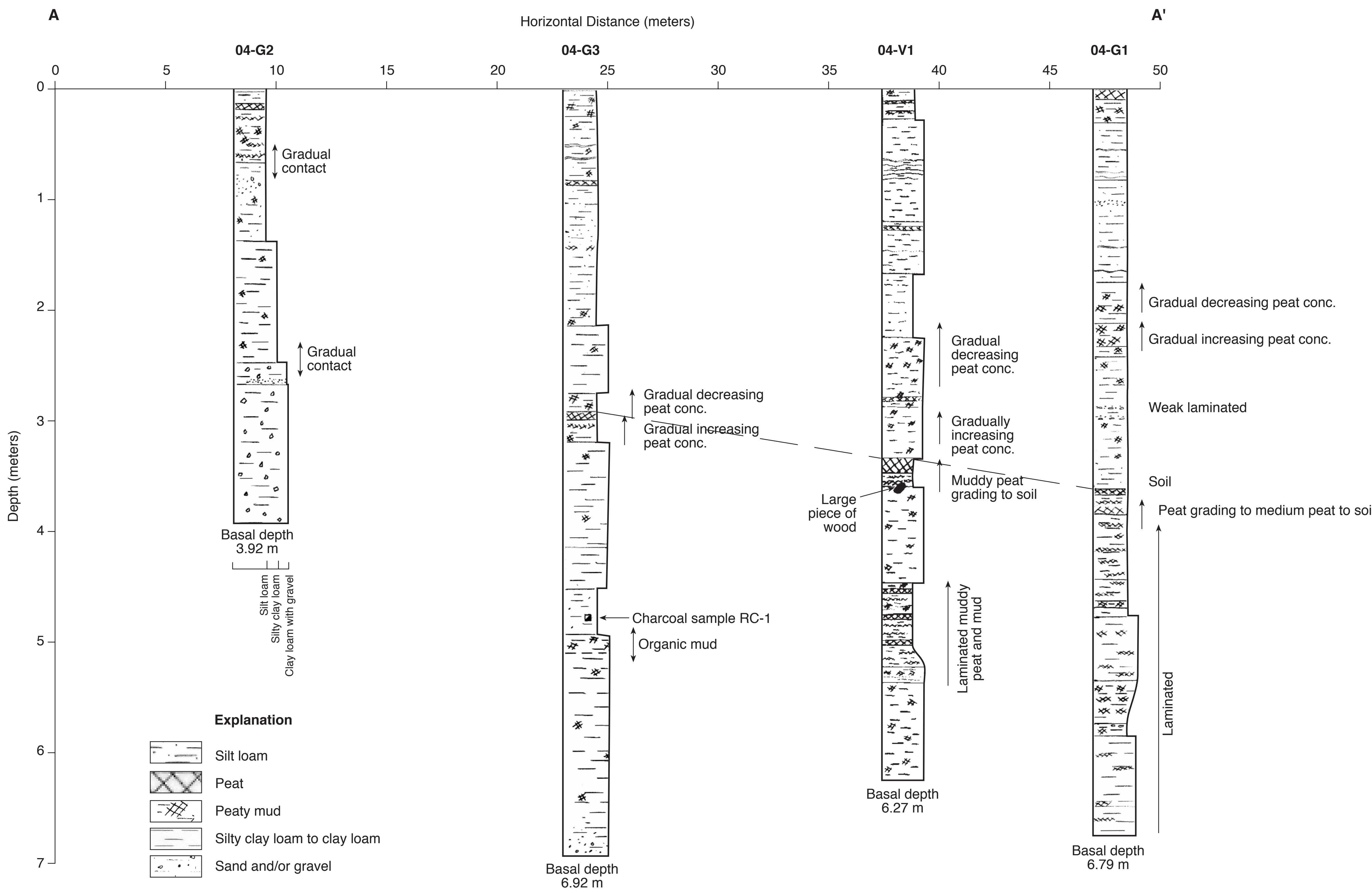


Figure 3. Map of northern part of China Camp State Park and tidal marsh located north of North San Pedro Road. Surficial geologic deposits were interpreted from 1:12,000-scale black and white aerial photography from 1992.



PILLAR POINT

Stratigraphic Cross Section for China Camp Marsh

WLA William Lettis & Associates, Inc.

Figure 4

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